FULL-SIZE PROTOTYPE OF ACTIVE THERMAL WINDOWS BASED ON THERMOELECTRICITY

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ABSTRACT

It is sometimes difficult to install air conditioning systems to control room temperature. One good example is during historic building restoration, where national or local laws may forbid installing air ducts or even just water pipes and heat exchangers. In such situation air-conditioning based on thermoelectricity may play an important role despite of a lower cooling performance compared with gas compression cycles. The proposal is to install window glasses with embedded thermoelectric elements that will transfer heat through the glass in order to heat or to cool the room.

After some previous experiences with small (10x10cm) prototypes, our team has developed and tested a full-size prototype of active thermal window (ATW) that is presented in this paper. The new prototype has been installed in a window frame (100x100cm) and will be able to generate up to 150W of cooling power while glass transparency is decreased in less than 20%.

The system includes automatic control in order to adjust voltage and current according to the measured room temperature, hence reducing electrical power consumption during normal use. Installation of the proposed air-conditioning system is as simple as replacing the current windows by the active version, in which just a pair of electric wires is required to run it in cooling or heating mode.

This project has been partially supported by the Spanish government through project no. BIA2004-06001.

Keywords: Thermoelectricity, Active thermal window, Air-conditioning

INTRODUCTION

Thermoelectricity can be used for electric power generation (Seebeck effect) or for heating/cooling applications (Peltier effect). Electric power generation has been very successful for specialized applications such as satellites [1], but also to generate electricity at remote places using gas heaters and to make use of wasted-heat sources at low temperature [2]. Cooling applications have only succeeded in low power applications such as camping coolers and small (hotel) refrigerators. For higher thermal power other cooling technologies overcome thermoelectricity by attaining better performance and lower prices.

TE camping coolers are successful because the lack of fluids and pumps makes TE option the most robust and reliable alternative for portable equipment. Moreover, the cost is low because just one module has enough power and no electronic controls or amplifiers are needed. TE coolers use a convenient 12V supply compatible with car outlets. A 50W module running during 5h produces the same cooling energy (900 kJ) as 2.7 kg (6 lb) of ice melting completely.

Hotel refrigerators are small and do not need much cooling power to keep some bottles just a few degrees cooler than the room temperature (usually no freezing temperatures are required). In this case reliability is not critical and performance still does not play an important role due to low power consumption, however the key factor it the absence of noise of the TE option.

Apparently, no TE-based air-conditioning solution could succeed in a market dominated by refrigeration cycles, where vapor-compression refrigeration is the most widely used method for air-conditioning of public places and residences. However, there are situations in which air-conditioning systems are difficult to install while a thermoelectric option may become worthy. This paper presents an Active Thermal Window that has been design to make air-conditioning available in buildings where typical pipes and ducts are not allowed or not suitable, for example in historic buildings.

PROTOTYPE DESCRIPTION

After the experience gained with smaller (10x10cm) prototypes in which thermoelectric pellets where manually installed in between two glass plates [3][4] a larger and more powerful system has been designed. A full-size prototype of active thermal windows has been built and installed in a 100x100cm frame. This prototype uses 30 commercial modules (Melcor CP1.0-63-05L) arranged in 5 columns comprising 6 modules each. The window is transparent except for 18.5% of the surface. TE modules are attached to heat exchangers on both sides to improve heat transfer to the air. The system is completely reversible and can be used to cool or heat the room just by changing the sign of the current.

All six modules within the same column are connected in electrical series, while the five columns are connected in parallel. The maximum theoretical power for each module would be $Qc=18.7W$, but this value can only be achieved for $\Delta T=0$. A more realistic situation would be to have $\Delta T=50$ºC, so using the module specifications it can be obtain that Qc would be 5W with electric supply of $V=6.5V$, $I=3A$ ($Qe= 19.5W$). For this condition ATW prototype will be able to produce the following values:

- Qc=150 W (cooling power)
- Qe=585 W (electrical power)
- Qh=735 W (heat to dissipate)

Two fans are used to force air-flow through heat exchangers at both sides of the window, but as it will be shown in the results the current configuration is not able to dissipate 700 W of heat at 50ºC

EXPERIMENTAL MEASUREMENTS

The system was supplied with DC current using two different power supplies, one for ventilators and another for the thermoelectric modules. Thermocouples are used to measure input and output temperature at the hot and cold sides of each column of modules; this means 20 signals. In addition, two sensors for room and for outside temperatures are used.

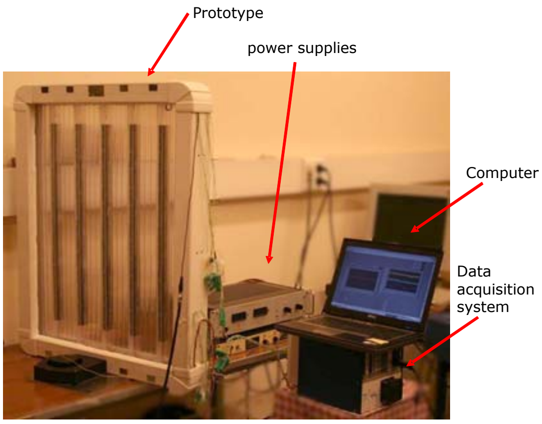

Figure 1: Experimental setup

Measurements are taken during the experiment using a National Instruments SCXI data acquisition system, and then they are stored in a laptop computer for post-processing. Figure 1 shows the prototype installed in the laboratory along with the instrumentation.

Different experiments where carried out in order to evaluate if the system was able to heat and cool the air properly. Therefore different values of the current have been tested and also the direction of the current has been reversed. As soon as the ATW is supplied with electrical current, the cold side begins to decrease the temperature. As it can be seen in the thermal image shown in Figure 2 (taken by infrared thermography), the coldest areas in the window correspond to the columns of heat exchangers that are mounted over the TE modules.

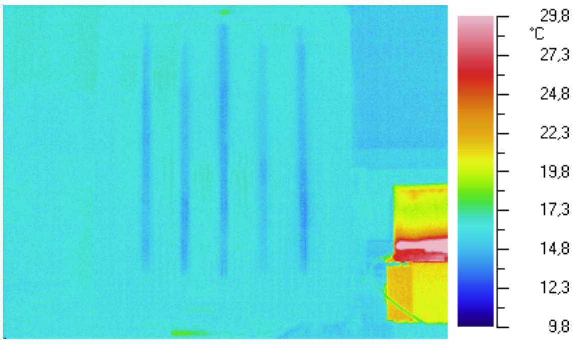

Figure 2: Thermal image of the prototype, seconds after connecting the modules

The response of the system is very fast, and even in the air which is flowing through the heat exchanger, temperature changes can be detected immediately after starting up the system. The evolution of air temperature, measured at two points in the hot side and at three points in the cold side, is shown in Figure 3. It takes just 4 minutes to reach a nearly steady-state in which the temperature of the air flowing off the window is increased or reduced 3 to 4 degrees with respect to the ambient temperature.

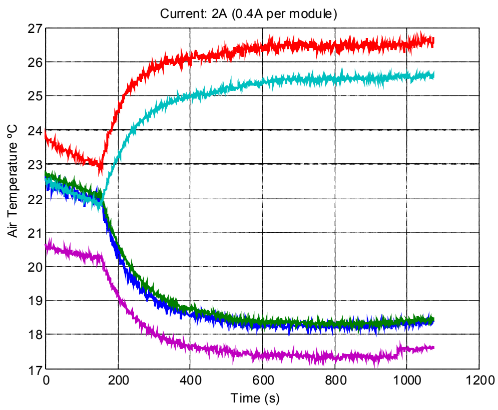

Figure 3: Temperature response. Heated air and cooled air

Figure 3 was generated by applying 2A to the system after 3 minutes in which only the ventilators were running. This current implies a voltage of 6.1V at the beginning of the experiment that increases to 6.5V as a consequence of temperature variations at the modules. Due to previously described electrical configuration, the voltage and current for each module are 0.4A and 1.08V. However the system was not run at higher power because the current configuration of heat exchanger and forced air flow does no have enough refrigeration capability.

Although the temperatures at the end of Figure 3 appear to be stabilized, it was found that there is not enough refrigeration capability at the hot side; as a consequence both temperatures keep increasing. At the hot side it is necessary to dissipate the heat absorbed at the cold side plus the electrical power supplied to the system, but when there is not enough dissipation capability the system maintains rather constant ΔT while increasing temperatures at both sides. This effect can be seen very clearly if Figure 4, also generated with a current of 2A but running the ventilators at a slower speed. All 22 temperatures where registered, but after an averaging process only three temperatures are shown: hot air, cold air and ambient temperature.

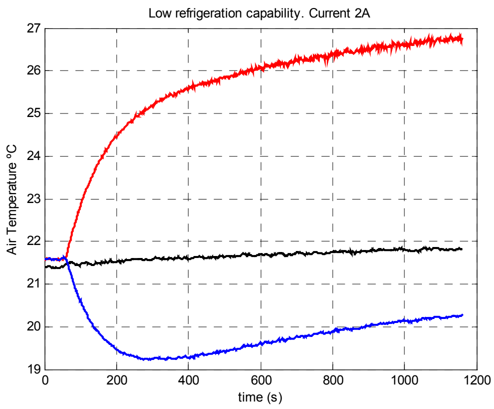

Figure 4: Result of undersized refrigeration

While the temperature increases, it is easier to transfer heat to the ambient, so eventually the system reaches a temperature in which it can dissipate all the power. By improving refrigeration, both temperatures would be reduced and it would also be possible to increase the current in order to increase ΔT.

TEMPERATURE CONTROL

In order to control the temperature of the cold air, it was found that the system could be modeled with high accuracy as a first-order system. Using the electrical current as the input and the cold air temperature at the outlet as the output variable, the static gain obtained by system identification is 1,475 ºC/A and the time constant is 97s.

The first order model of the system allowed us to create a closed-loop control. First a proportional control strategy was applied with satisfactory results. Still, the control was improved by adding an integral term (PI scheme) since it is well known that proportional control yields a non-zero offset error between the attained output temperature and the requested temperature, in steady-state.

The PI closed-loop controller finally implemented (Figure 5) includes some blocks for conditional integration, in order to avoid windup effect that may appear if the control effort has limits.

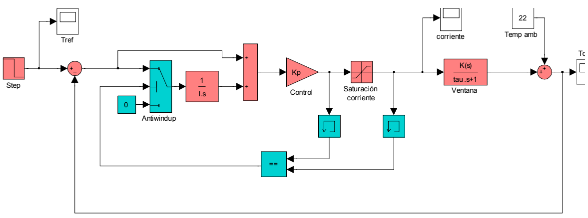

Figure 5: Closed-loop temperature control

Figure 6 shows the results of the controlled response. It can be seen that there is no error once the steady-state is reached. In this case the system is stabilized in about 3 minutes, but since the current was limited to 4A, stabilization time would be larger if the requested temperature change is larger.

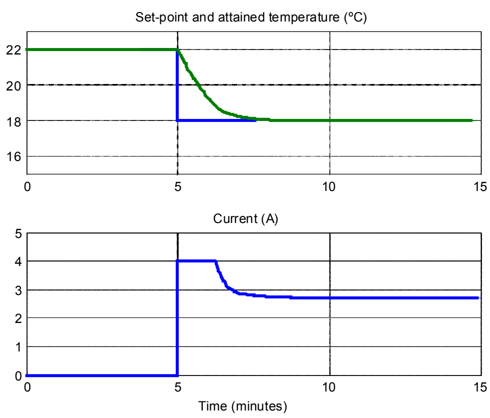

Figure 6: Dynamic response of the PI controller

CONCLUSION

A prototype of an Active Thermal Window has been built and tested in the laboratory. Although the current configuration of heat exchangers and air flow do not permit running the system at full power, it has a potential refrigeration power of 150W per square meter with just 20% vision blocking.

The Active Thermal Window, which is protected by a Patent issued by Universidad Pontificia Comillas, may not compete in performance with standard refrigeration cycles. However it has the advantage of installation simplicity that is remarkable in historic building restoration as well as in other environments. This additional benefit may make this particular application of thermoelectricity as successful as TE camping coolers or hotel refrigerators.

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